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SUMMARY

ROCKETDYNE
A DIVISION OF NORTH AMERICAN AVIATION, INC.
6633 CANOGA AVENUE, CANOGA PARK, CALIFORNIA

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32

R-5751

INVESTIGATION OF ENGINE-COMPONENT INTEGRATION

SUMMARY
VOLUME 1
FINAL REPORT

GROUP-4
Downgraded at 3 year intervals;
declassified after 12 years

ROCKETDYNE
A DIVISION OF NORTH AMERICAN AVIATION, INC.
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CANOGA PARK, CALIFORNIA

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FOREWORD

This report was prepared in compliance with the requirements for the National Aeronautics and Space Administration Contract, NAS 8-4001, Investigation of Engine-Component Integration Study. Technical monitors have been the Liquid Propulsion Systems office at NASA headquarters and the Engine Systems branch at the Marshall Space Flight Center.

ABSTRACT

(Unclassified Abstract)

1667

The analyses and results of the investigations conducted under the National Aeronautics and Space Administration Contract, NAS 8-4001, Investigation of Engine-Component Integration Study, are summarized in this report. Component concepts for functional and packaging integration were investigated for spacecraft and boosters. Spacecraft propellant combinations considered were O_2/H_2, F_2/H_2, and N_2O_4/N_2H_4-UDMH(50-50); booster propellants were O_2/H_2 and O_2/RP-1. Evaluations were made of a number of system concepts, with and without turbopumps. Preliminary-design layouts were made of the more-promising concepts.

AUTHOR

INTRODUCTION

The superior simplicity and reliability of pressure-fed systems are frequently the reasons for their selection in applications which would otherwise suggest the use of pump-fed systems. Examples of such applications are those wherein small propulsion-system volumes and/or long firing durations are desirable (or required), but the additional requirements of maximum simplicity and reliability preclude the use of typical pump-fed systems.

This study was initiated to investigate methods of making pump-fed systems more competitive with the simplicity of pressure-fed systems, and to investigate other concepts which could possess the desirable characteristics of both pump-fed and pressure-fed systems, but would not necessarily use conventional methods of pumping.

OBJECTIVES AND SCOPE

The general objective of this study has been to evolve system concepts which could possess, in some measure, the high-chamber-pressure capability (small envelope) of pump-fed systems, and yet be simpler and more reliable than existing pump-fed systems. The primary mechanism which was to be used to effect this objective was component integration -- both physical integration and functional integration.

More specifically the objective was to evolve systems which, because of their more efficient use of volume; possess greater operational-simplicity, lower weights, and higher reliabilities than can be attained by conventional pump-fed systems.

Concepts to be investigated were to be applicable to advanced booster systems using LO_2/LH_2 and LO_2/RP-1; and to spacecraft systems using LO_2/LH_2, LF_2/LH_2 and N_2O_4/N_2H_4-UDMH(50-50) as propellants. Spacecraft systems were to be considered for both conventional and advanced nozzles.

The more-promising system and/or component concepts were to be selected for preliminary design and layout.

GENERAL METHOD OF APPROACH

The general method of approach was to first minimize system complexity through functional analysis and integration, and then to investigate methods of physically integrating the required components. Emphasis for this latter phase was on component integration; however, component integration cannot be completely separated from system integration, so a part of this effort has consisted of system integration, i.e., definition of the over-all engine configuration.

The functional analysis and integration effort consisted, in part, of compiling operational data on a large number of existing pump-fed propulsion systems, and arranging these data into a "morphological" chart (Figure 1). The purpose of this chart is twofold: (1) It provides a simple means of manipulating existing concepts to form novel combinations which might prove to be significantly better than existing configurations, and (2) It is an aid in evolving novel concepts, for it indicates what is inherent in a pump-fed system, and what is just a function of some particular design. The headings to the extreme left of the chart indicate there are essentially three things that all pump-fed systems require, namely, a feed system, an ignition system, and a control system. Thus, effort on the evolution of new concepts should be directed at novel methods of performing these three basic functions.

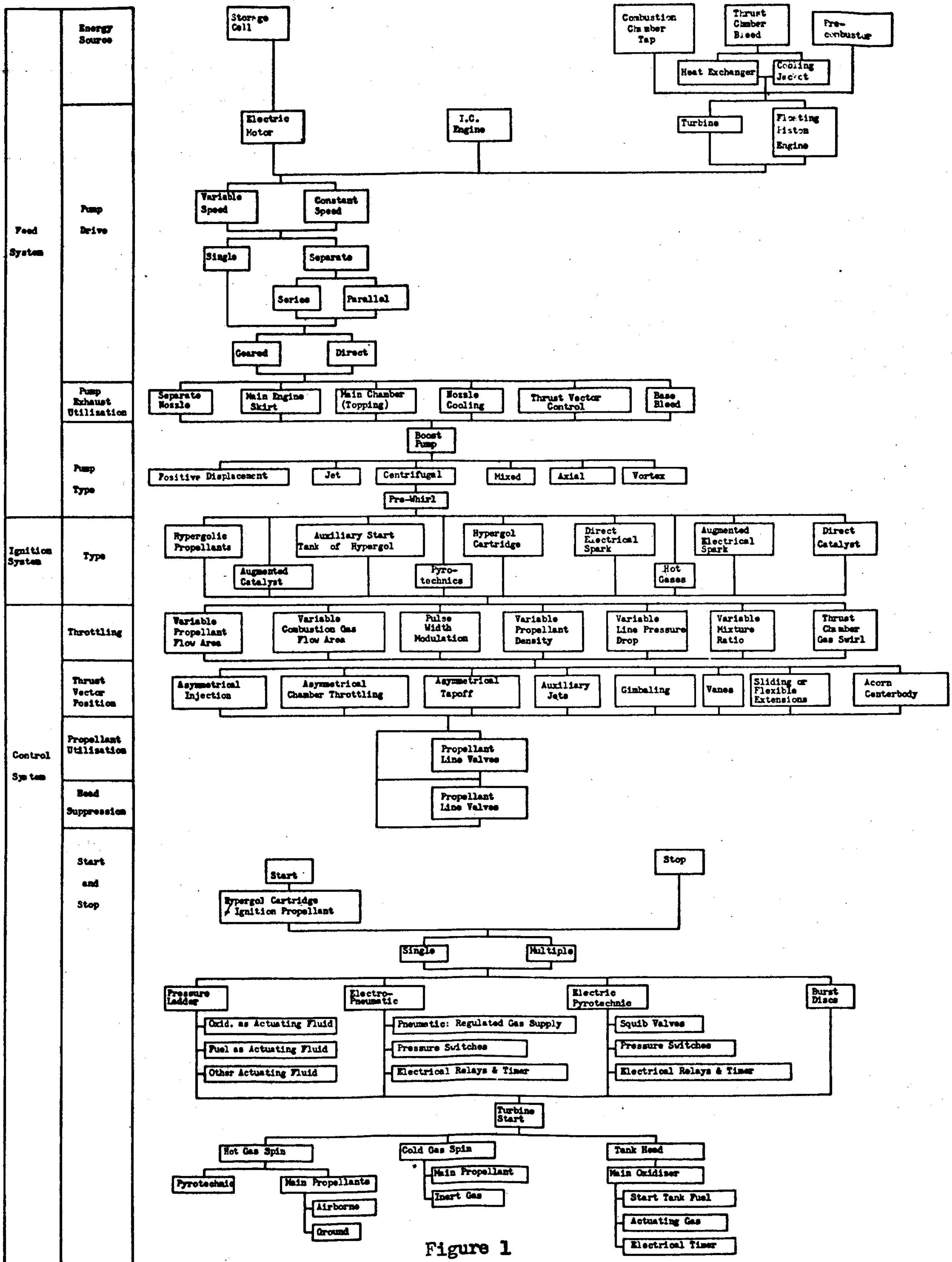

Feed System
Energy Source
Storage Cell
Combustion Chamber Tap
Thrust Chamber Bleed
Pre-combustor
Heat Exchanger
Cooling Jacket
Electric Motor
I.C. Engine
Turbine
Floating Piston Engine
Pump Drive
Variable Speed
Constant Speed
Single
Separate
Series
Parallel
Geared
Direct
Pump Exhaust Utilization
Separate Nozzle
Main Engine Skirt
Main Chamber (Topping)
Nozzle Cooling
Thrust Vector Control
Base Bleed
Boost Pump
Pump Type
Positive Displacement
Jet
Centrifugal
Mixed
Axial
Vortex
Pre-Whirl
Ignition System
Type
Hypergolic Propellants
Auxiliary Start Tank of Hypergol
Hypergol Cartridge
Direct Electrical Spark
Augmented Electrical Spark
Direct Catalyst
Augmented Catalyst
Pyro-technics
Hot Gases
Control System
Throttling
Variable Propellant Flow Area
Variable Combustion Gas Flow Area
Pulse Width Modulation
Variable Propellant Density
Variable Line Pressure Drop
Variable Mixture Ratio
Thrust Chamber Gas Swirl
Thrust Vector Position
Asymmetrical Injection
Asymmetrical Chamber Throttling
Asymmetrical Tapoff
Auxiliary Jets
Gimbaling
Vanes
Sliding or Flexible Extensions
Acorn Centerbody
Propellant Utilization
Propellant Line Valves
Head Suppression
Propellant Line Valves
Start and Stop
Start
Stop
Hypergol Cartridge / Ignition Propellant
Single
Multiple
Pressure Ladder
Electro-Pneumatic
Electric Pyrotechnic
Burst Discs
Oxid. as Actuating Fluid
Fuel as Actuating Fluid
Other Actuating Fluid
Pneumatic: Regulated Gas Supply
Pressure Switches
Electrical Relays & Timer
Squib Valves
Pressure Switches
Electrical Relays & Timer
Turbine Start
Hot Gas Spin
Cold Gas Spin
Tank Head
Pyrotechnic
Main Propellants
Airborne
Ground
Main Propellant
Inert Gas
Main Oxidizer
Start Tank Fuel
Actuating Gas
Electrical Timer

Figure 1

The investigation of concepts possessing the desirable characteristics of both pump-fed and pressure-fed systems, but not using conventional pumping methods, was similarly directed.

MORE-PROMISING CONCEPTS

The more-promising concepts have been selected in three categories:

(1) System concepts with turbopumps

(2) System concepts without turbopumps

(3) Component concepts

Most concepts were evolved for specific propellants and thrust levels (spacecraft or booster), however, their use is not necessarily restricted to these applications. The applicability of each concept to all propellants and thrust levels within the scope of this program has been considered, and the conditions required for applicability in the various areas are indicated.

The more-promising system concepts were selected on the basis of ratings for operational simplicity, weight, and reliability (see Vol. II).

SYSTEM CONCEPTS WITH TURBOPUMPS

The selected functional configurations for systems using turbopumps are discussed below. The discussion includes system operational characteristics and advantages, as well as preliminary-design layouts of possible engine-system packages.

Spacecraft

Figure 2 contains schematics of the selected functional spacecraft systems for the following propellants:

(1) O_2/H_2 (system 101)

(2) F_2/H_2 (system 201)

(3) NTO/50-50 (system 307)

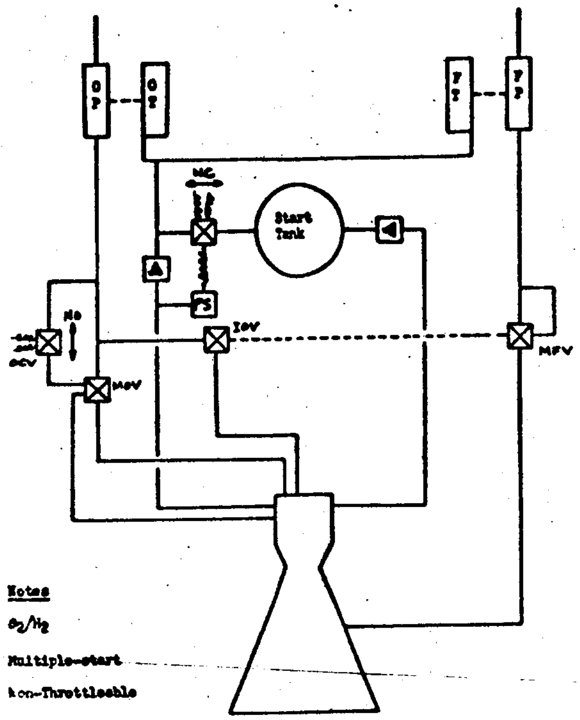
All of these systems derive much of their simplicity from the use of propellant-actuated valves, and the thrust chamber tap-off concept for a turbine power source. The use of propellant-actuated valves has been proven using non-cryogenic fluids (for example, Rocketdyne's H-1 engine). This method of actuation for cryogenics is novel and provides a significant simplification for systems wherein both propellants are cryogenic.

A brief description of the operational sequence for system 101 is given below; operation of the other systems is similar.

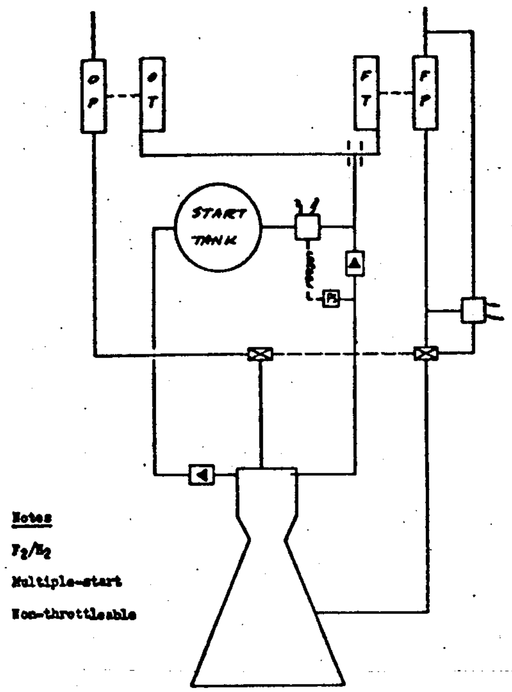
The primary events in the start sequence for system 101 are as follows:

(1) Electrical start signal opens the normally closed start-tank valve (STV), and closes the normally open oxidizer cut-off valve (OCV)

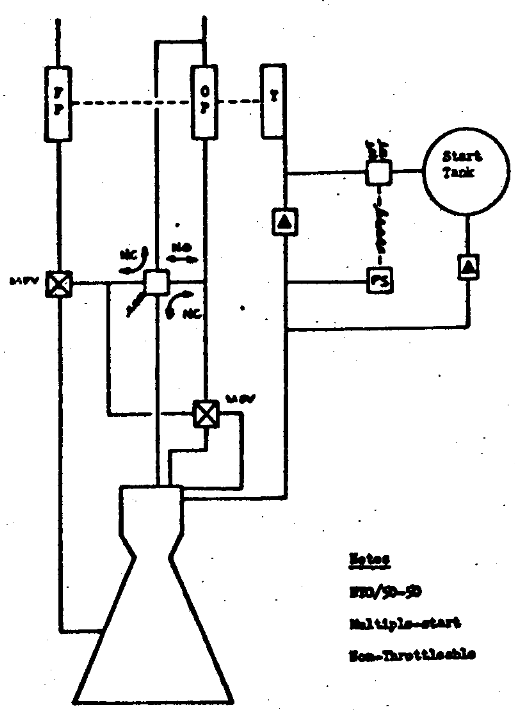
(2) Gas from the start tank accelerates the turbopumps and pressure starts to buildup in the main lines.



System 101



System 201



System 307

Spacecraft System Schematics

Figure 2

(3) Main fuel valve (MFV) is opened by fuel pressure in the main line; the igniter-oxidizer valve (mechanically linked to the main fuel valve) is opened; lines start to prime, and propellants start to burn in the catalytic ignition-chamber.

(4) Ignition stage is achieved.

(5) Ignition-stage chamber-pressure opens the main oxidizer valve, and chamber pressure starts to rise.

(6) Pressure switch (PS) in the tap-off line is actuated by the pressure from the chamber indicating the system is ready to bootstrap; actuation of this switch (which is electrically linked to the start-tank valve) de-energizes (closes) the start-tank valve (STV).

(7) The system bootstraps, and mainstage ensues.

(8) The start-tank is refilled from the thrust-chamber cooling jacket.

The cut-off sequence is:

(1) Cut-off signal de-energizes two solenoid valves: the oxidizer cut-off valve (OCV), and the start-tank valve; the latter was already de-energized by the pressure switch in the tap-off line, but this additional open switch in the circuit is required to prevent the valve from opening when the pressure switch is deactuated by decaying tap-off pressure.

(2) De-energizing the OCV sends oxidizer to the closing ports of the MOV, thus closing it.

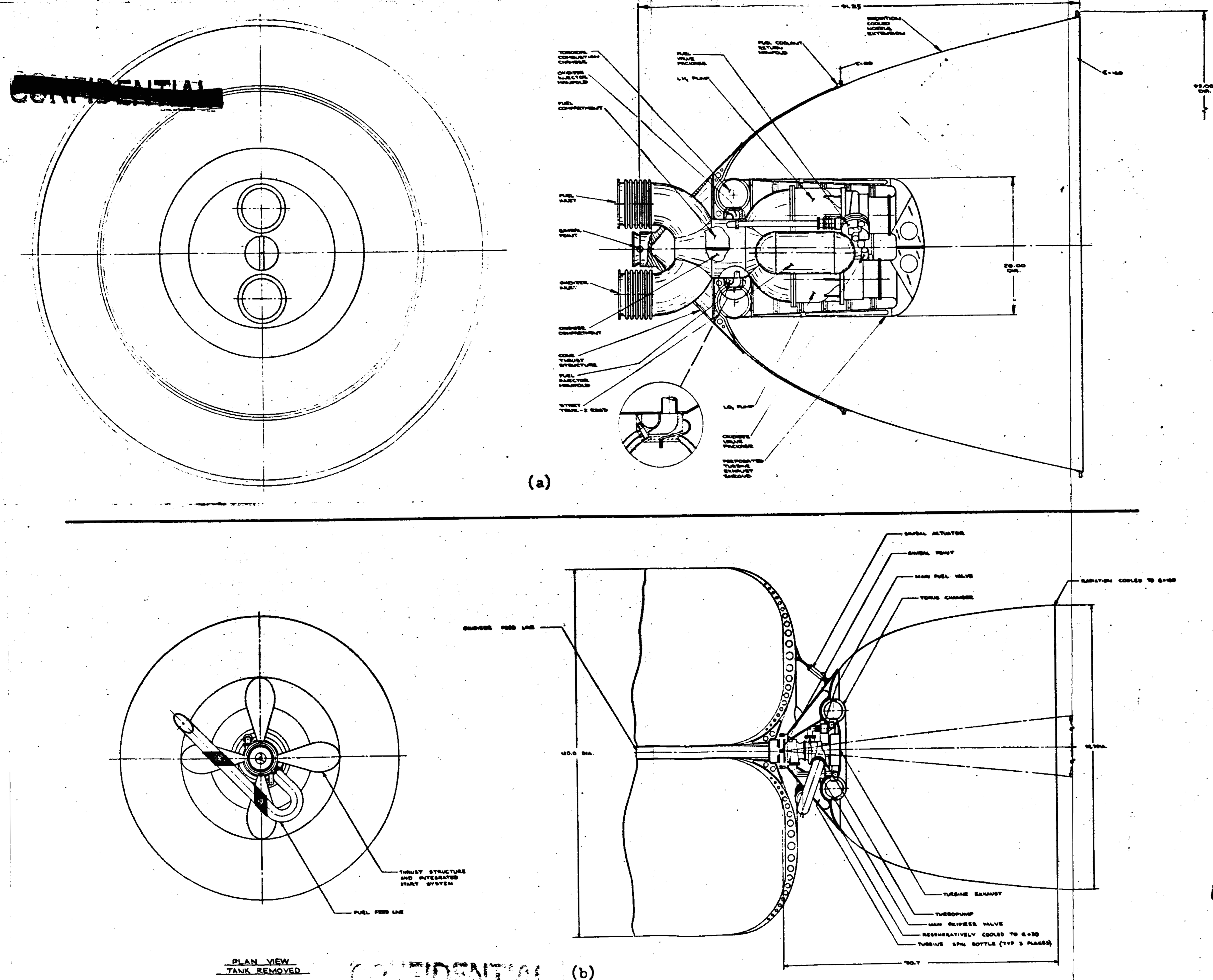
(3) Chamber pressure decays, and the main fuel valve closes; cut-off is effected.

Figures 3 and 4 contain typical, integrated, over-all spacecraft engine configurations.

The systems shown in Figure 3 are representative of low-thrust (approximately 40 K advanced-nozzle, spacecraft engines. Figure 3 (a) is for systems using dual-shaft turbopumps, for example, O_2/H_2 or F_2/H_2 systems; Figure 3 (b) is for systems using single-shaft turbopumps, for example, NTO/50-50 systems. Figure 4 shows representative configurations for the same type engines using bell thrust chambers.

The O_2/H_2 spacecraft systems (multiple-start) have a simplified ignition system based on the use of a catalytically ignited mixture of O_2/H_2. The O_2/H_2 igniter flow is passed through a catalyst pack whereupon it ignites, thus providing an ignition method for the main flow which approaches the simplicity of hypergolic systems.

The NTO/50-50 systems are further simplified by use of a novel start method, namely, a stored-gas spin-start system using stored gases which are obtained from the thrust-chamber tap-off line during engine operation.

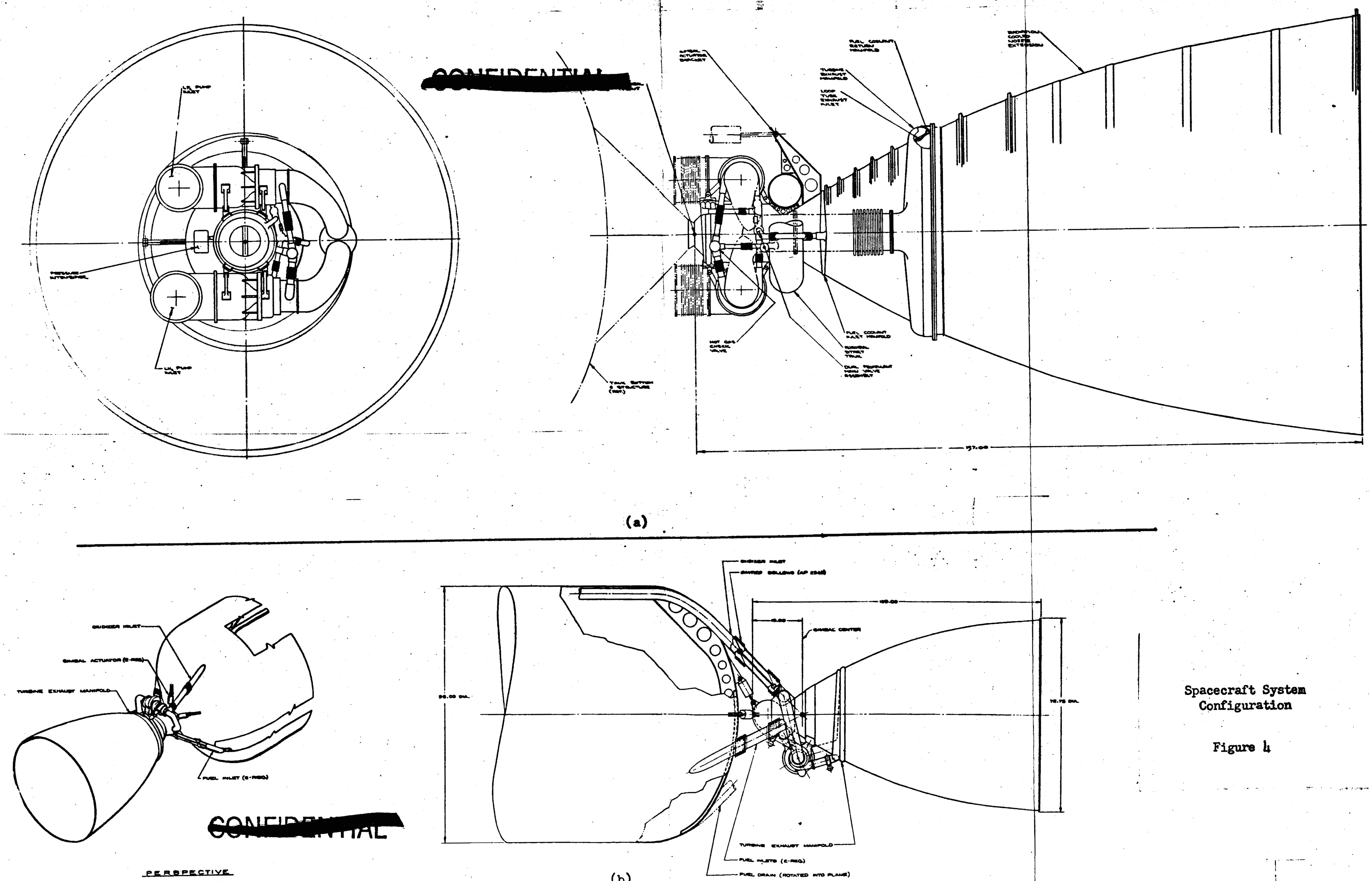


(a)

(b)

Spacecraft System Configuration

Figure 3



Spacecraft System Configuration

Figure 4

Results of the start-system analysis conducted as a part of this program indicate this is a feasible method of achieving a multiple-start capability for NTO/50-50 systems (see Vol. II).

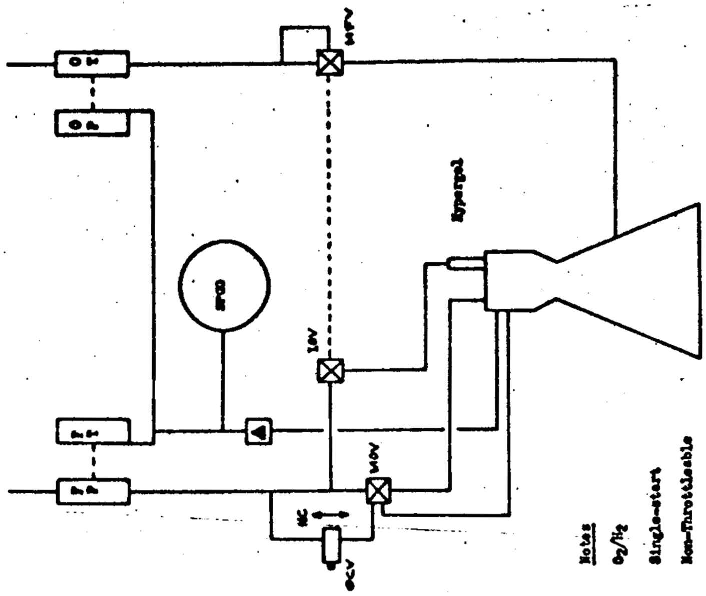
Boosters

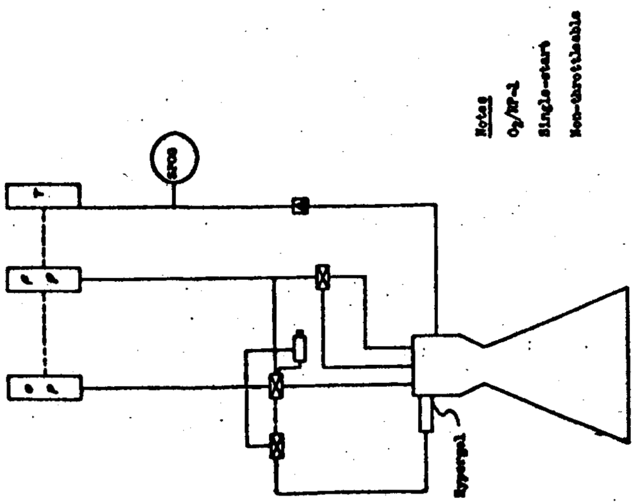
Schematics of the selected functional booster systems which are for the O_2/H_2 (system 103) and O_2/RP-1 (system 401) propellant combinations are shown in Figure 5 .

These systems are similar to the spacecraft systems in that the use of propellant-actuated valves and the tap-off concept are the primary factors contributing to system simplification.

The operational sequences for systems 103 (O_2/H_2) and 401 (O_2/RP-1) are similar. These sequences are very much like that for system 101; the notable differences are: (1) a solid-propellant gas-generator is used to start the turbopump(s) instead of stored gas, (2) ignition is accomplished using a hypergolic slug instead of catalytic ignition, and (3) the oxidizer cut-off valve is a pyrotechnic valve rather than a solenoid valve. These differences result from the fact that only one start is usually required for booster application.

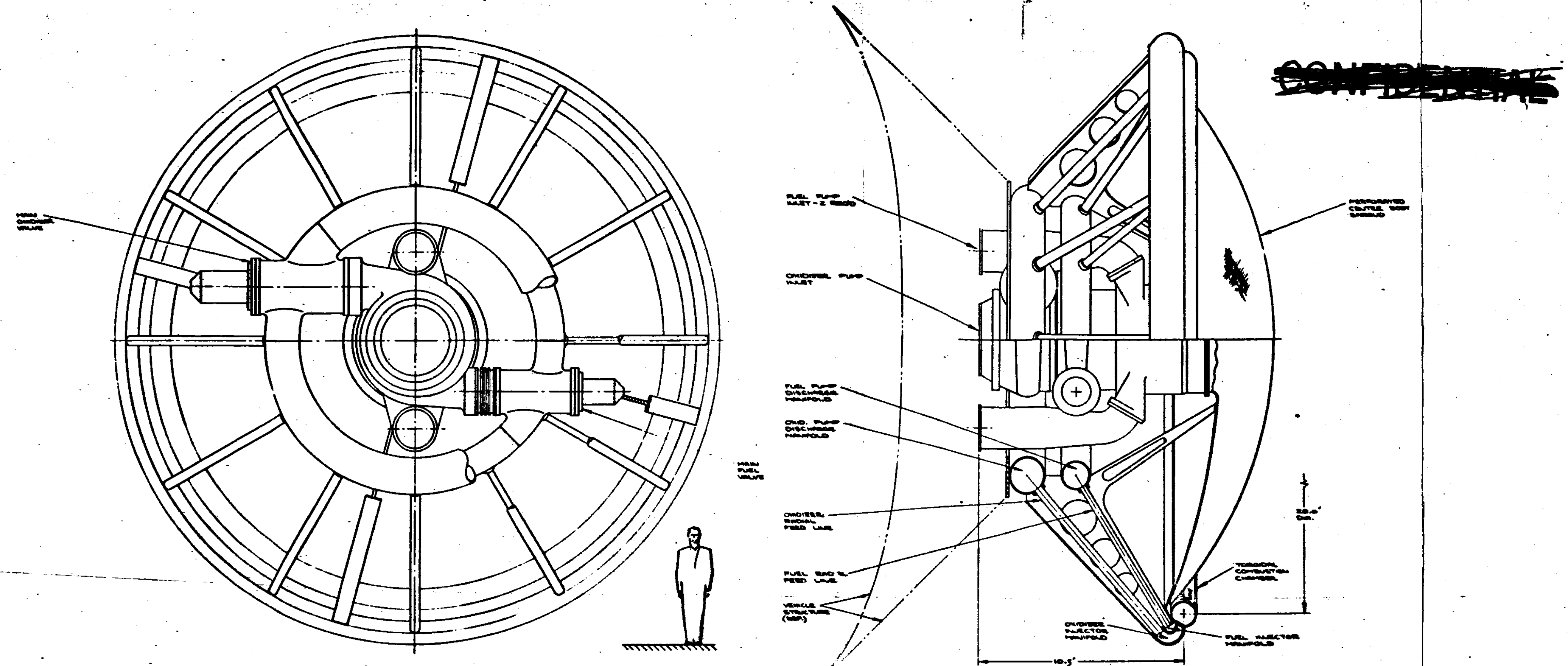
Figure 6 shows representative configurations for high-thrust (approximately 6M), integrated, over-all engine configurations; both concepts utilize the aerodynamic-spike advanced-nozzle concept (Ref. 1).



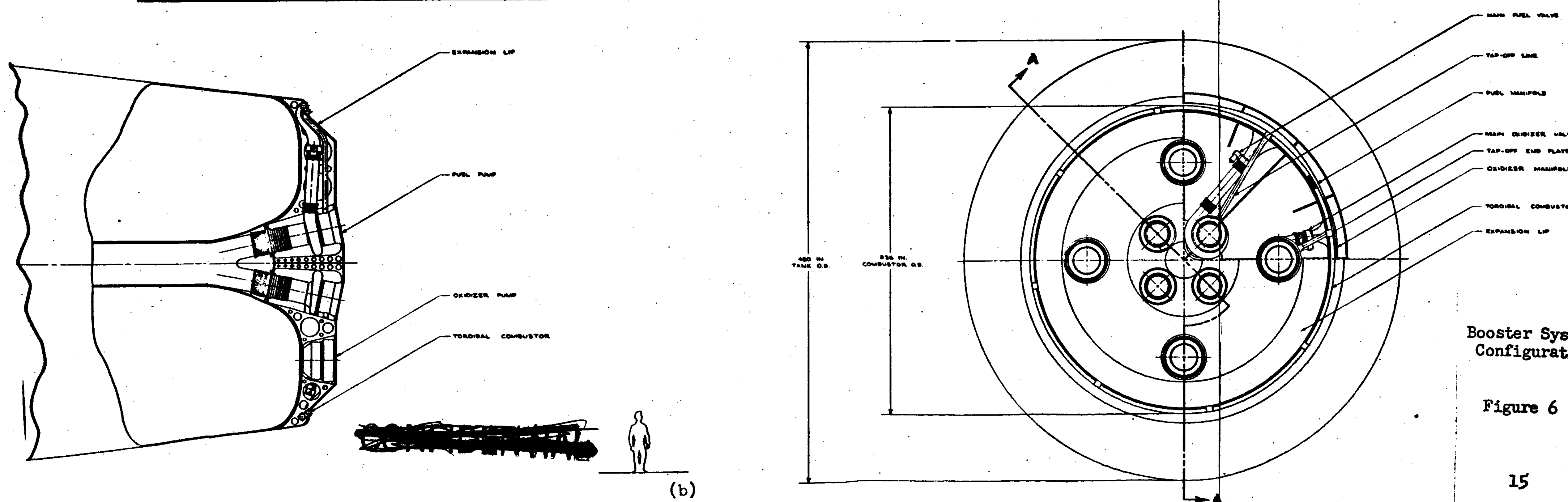


Booster System Schematics

Figure 5



(a)



(b)

Booster System Configuration

Figure 6

Figure 6 (a) is for a single turbopump, single-shaft pump system (O_2/RP-1); whereas Figure 6 (b) is for a multiple turbopump (4), dual-shaft pump system (O_2/H_2). It should be noted that the optimum number of pumps has not been determined for either of these propellant combinations as a part of this program. The numbers of pumps for the systems shown in Figure 6 were selected arbitrarily with the intent being to contrast single-pump and multiple-pump system-configurations.

To recapitulate, it has been shown in this section how the following could be functionally integrated, and packaged into compact engine-system configurations

(1) Thrust chamber and turbine-drive power source (tap-off),

(2) Ignition system and main-propellant system (catalytic ignition - - O_2/H_2 systems),

(3) Valve-actuation system and main-propellant system (propellant actuated valves, especially those actuated with cryogenic fluids),

(4) System valves (through use of mechanical and fluid interconnections wherever possible), and

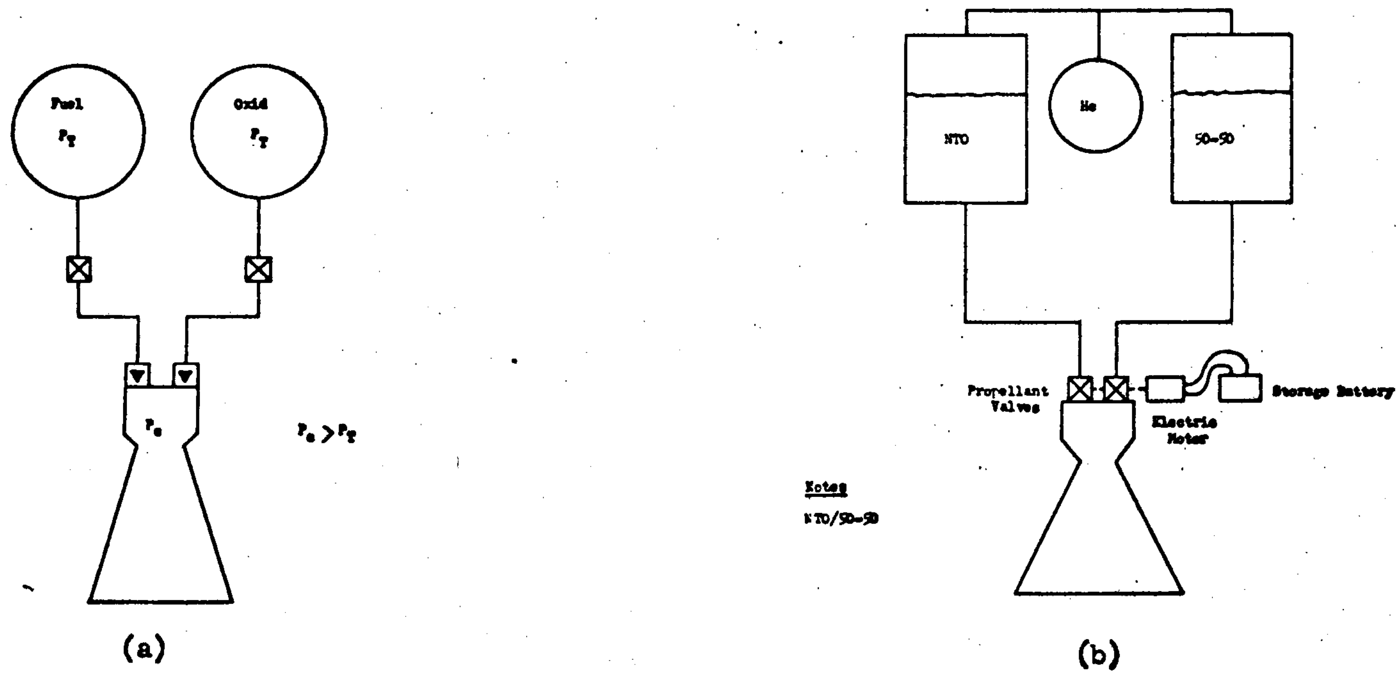
(5) Start system and steady-state turbine-drive system (tap-off gas-spin start - - NTO/50-50 systems).

SYSTEM CONCEPT WITHOUT TURBOPUMPS

Part of this study was directed at evolving concepts having high-chamber pressure capability, but not having the complexity usually associated with the use of turbopumps. As used above, high chamber pressure means higher than would be practical for a conventional pressure-fed system. A number of such concepts was investigated and evaluated; the most promising of these is the pulsing engine.

Pulsing Engine

The pulsing engine is a pressure-fed, high chamber-pressure, low tank-pressure, pulsing engine. The primary features of the engine are check valves near the injector, and main propellant-valves (Figure 7 (a)). The check valves are sized so a "large" amount of propellant flows into the chamber before chamber pressure builds up enough to close the check valves. The propellant burns and the chamber pressure builds up to a large value (considerably greater than tank pressure) which closes the check valves. Chamber pressure decays, the check valves open, and the cycle is repeated. This configuration probably represents the simplest form this concept could assume. A slightly less simple configuration, Figure 7 (b) should be easier to test and develope. This configuration operates in a similar fashion; the only difference being that propellant flow is regulated by an electrically actuated valve. The latter system



Pulsing Engine Schematics

Figure 7

was used in making a payload comparison with a pressure-fed system (see Vol. II). The results of this comparison indicate the pulsing engine has a small payload advantage (approximately 2.5% for $\Delta V = 10{,}000$ f.p.s.) and a substantial size advantage, Figure 8.

Although it is difficult to assign a meaningful reliability to this concept because of its novelty and the lack of applicable test data, indications are that it should be significantly more reliable than a conventional pump-fed system.

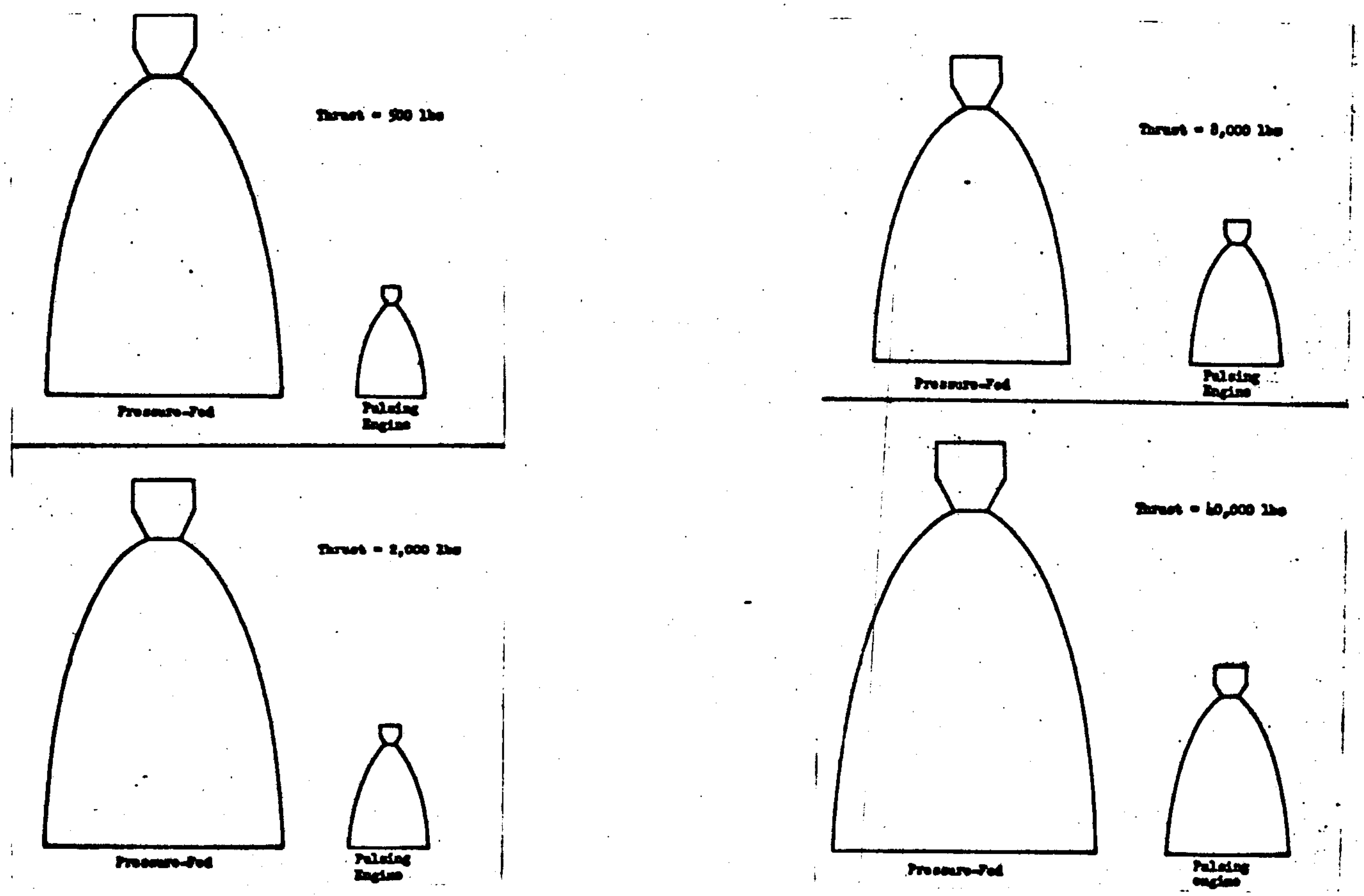
COMPONENT CONCEPTS

A number of component concepts has been evolved and evaluated. The more promising of these are:

(1) Propellant-actuated valves (especially for systems wherein both propellants are cryogenic).

(2) A concept for integrating multiple-poppet main-propellant valves in injectors,

(3) A "three-leg" gimbal system which integrates the gimbaling device, thrust structure, and propellant ducts.



Note: Based on same time-average thrust

Size Comparison, Pressure-Fed and Pulsing Engines

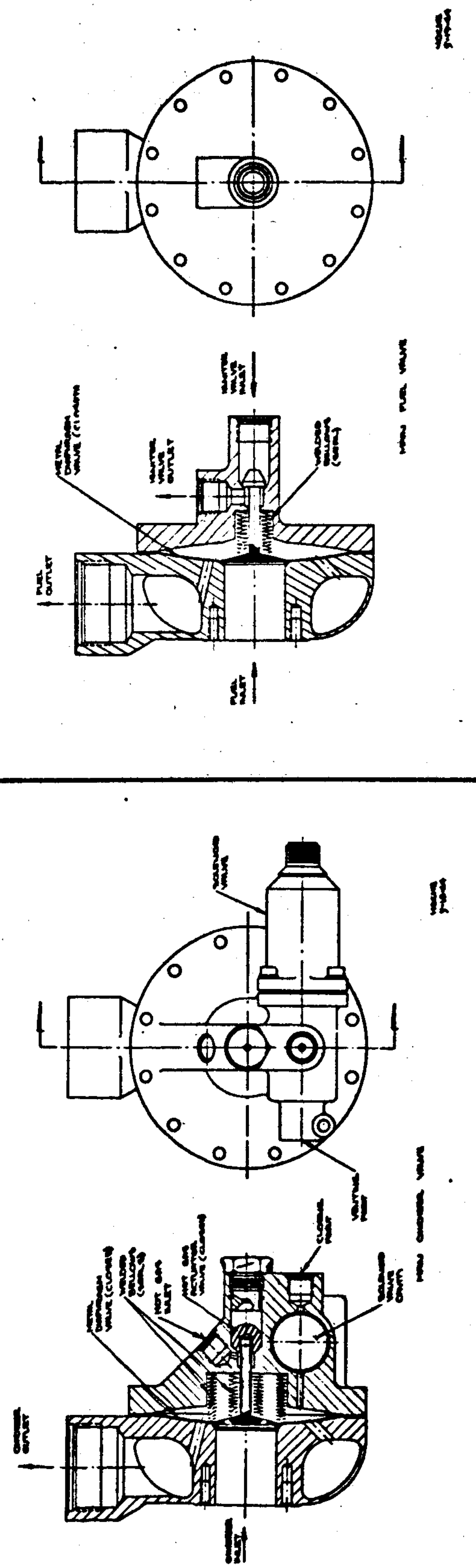
Figure 8

Cryogenic-Actuated Valves

Figures 9 and 10 contain layouts of some propellant-actuated valve configurations; these configurations implement the functional integration discussed above (see Vol. II for operational details); the valves in Figure 9 were evolved for an O_2/H_2 system, those of Figure 10 for an NTO/50-50 system.

Multiple-Poppet Main-Valves

The selected multiple-poppet main-propellant valve concept (Figure 11) is more advantageous for large engine-systems, that is, systems having propellant flowrates large enough that use of a single valve for each propellant could present serious packaging and propellant-distribution problems. In addition to the advantages of compactness and simplicity, these valves have no low-leakage dynamic seals. The only real seal is a static seal, A Figure 11(a); leakage around the poppet is simply returned to the pump-inlet through the pilot manifold. The poppets are held closed by main-line propellant pressure at B (Figure 11(a)) and the springs. Venting the pressure at B allows the same pressure at C to open the valves.

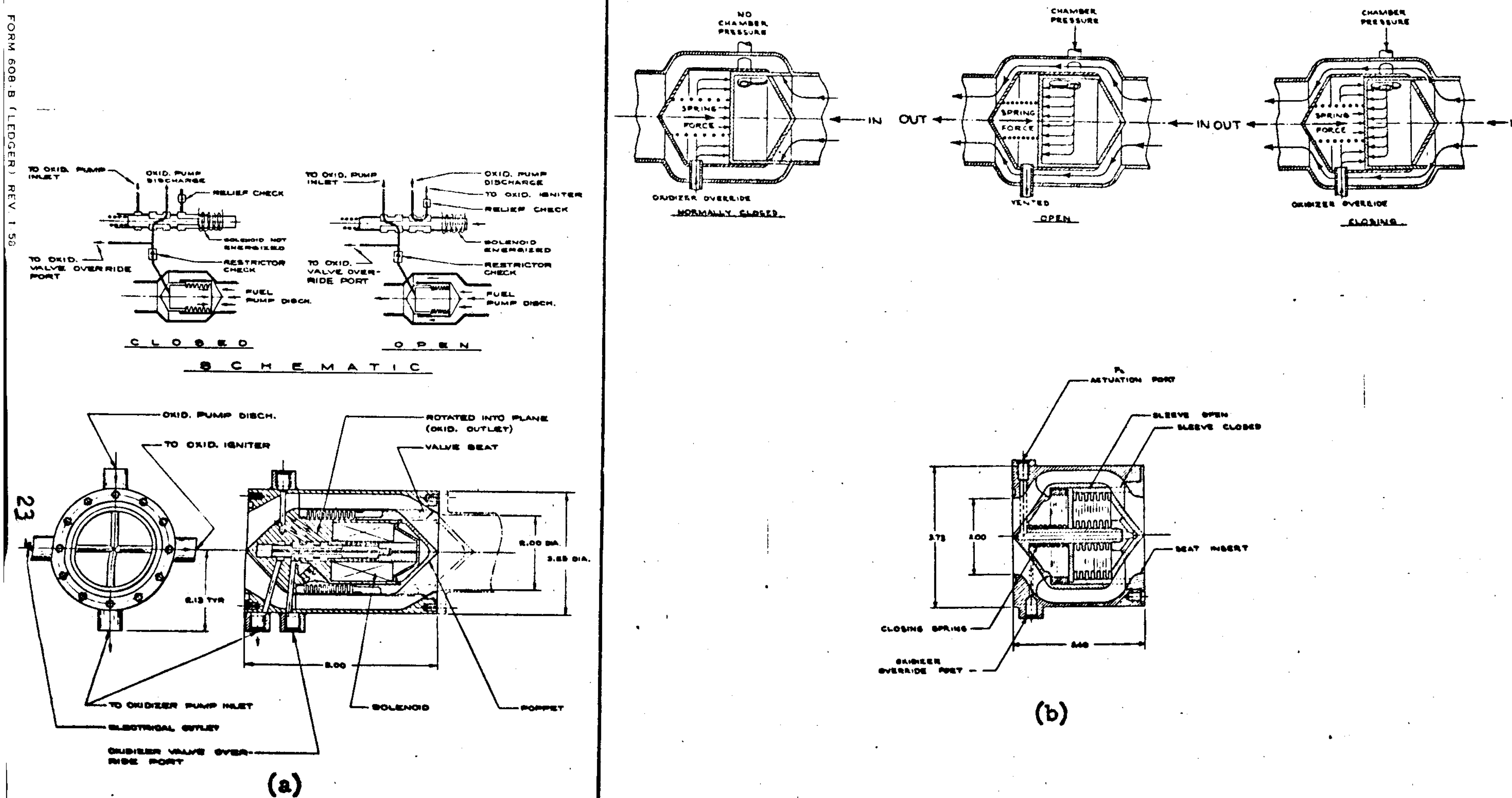


(b)

(a)

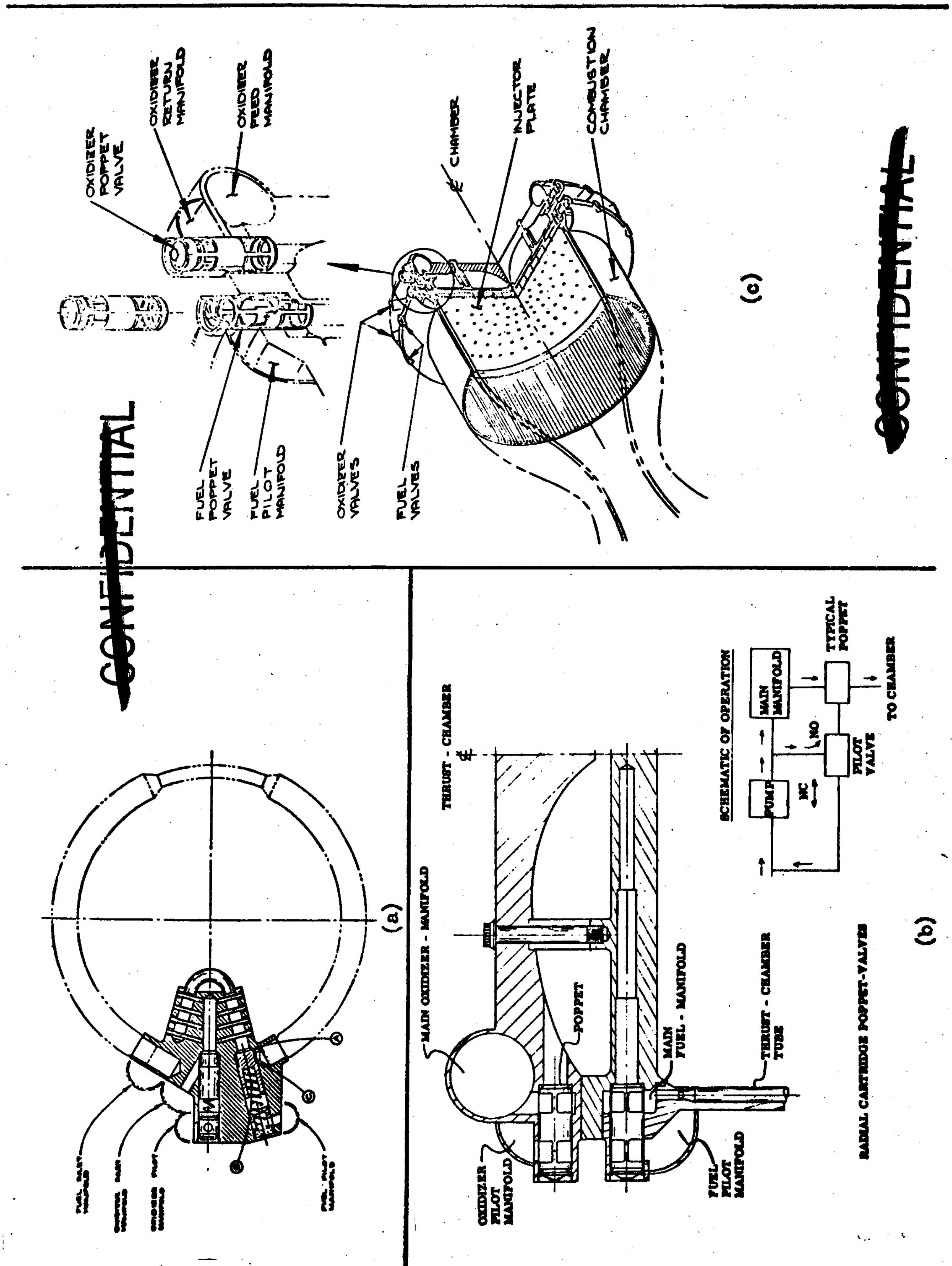
Propellant-Actuated Valves, O_2/H_2

Figure 9



Propellant-Actuated Valves, NTO/50-50

Figure 10



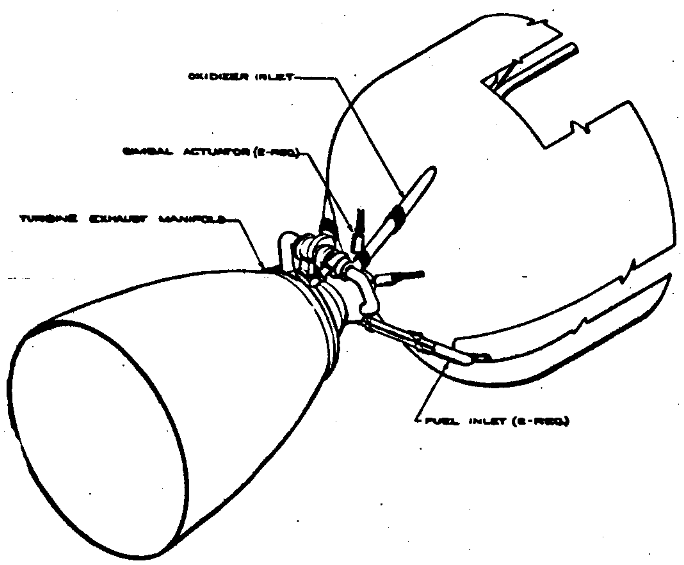
Multiple-Poppet Main-Valves

Figure 11

Three-Leg Gimbal

The "three-leg gimbal" concept integrates the gimbal bearing, thrust structure, and propellant inlet ducts as shown in Figure 12. This places the gimbal point closer to the engine center of gravity, thus reducing the required actuator loads. It should also be lighter and more compact than the components it replaces.

As shown, the "three-leg" gimbal utilizes the "canted" bellows concept. This concept allows a flexible joint in a propellant line to bend about axes other than those perpendicular to the propellant-line axis. This concept is discussed further in the section on suggested additional work.



PERSPECTIVE

Three-Leg Gimbal Installation

Figure 12

SUGGESTED ADDITIONAL WORK

The potential advantages associated with the use of several of the more-promising concepts described above are attractive enough to warrant further analytical and/or experimental investigations to verify their feasibility, and to obtain better estimates of their potential. Brief outlines are presented below for investigations that would help establish the value of a number of these concepts. These concepts are:

(1) Actuation of main-propellant valves using cryogenic fluids,

(2) Use of stored tap-off gases for gas-spin start of NTO/50-50 multiple-start systems

(3) "Three-leg" gimbal system

(4) Pulsing engine

The outlines presented are intended to describe general approaches to the investigation of these concepts that would uncover any major shortcomings as quickly as possible. That is, the intent has been to outline efficient, modest-cost, investigation programs for these concepts.

CRYOGENIC-ACTUATED VALVES

Using a non-cryogenic main-propellant to actuate valves has proven to be a simple and reliable method of actuation for Rocketdyne's H-1 engine. The same advantages apparently exist for valve actuation with cryogenic propellants. Rocketdyne's use of a small cryogenic-actuated control valve has been successful; however, this valve is too small and its actuation stroke too short to make extrapolation of this success to cryogenic-actuated main propellant valves reasonable.

Investigation of cryogenic-actuated main valves is ideally suited to a program apart from the development of a complete propulsion system. The reason for this is that despite the advantages of the concept, there is enought uncertainty about its applicability to a complete propulsion system to make its inclusion as part of a proposed system premature.

A combined analytical and experimental program to evaluate this concept would be directed at answering the following questions:

(1) Can valves be satisfactorily actuated using cryogenics?,

(2) If the valves must be pre-conditioned before actuation, is the required pre-conditioning practical in a system application?

The over-all objectives of the investigation could be to formulate an analytical model of cryogenic-actuated valves, and to conduct a limited experimental investigation for use in developing and/or verifying the validity of the model. Ultimately the model could be extended to the analysis of complete systems using cryogenic-actuated valves. Such a model should be useful in determining which cryogenic fluids could be used for valve actuation. It could also provide the design information required for efficient design of this type of valve.

The experimental portion of the investigation could initially consist of the re-design and testing of an existing propellant-actuated valve, so it could be cryogenic-actuated. This could provide a comparatively rapid means of getting an indication of whether or not cryogenic-actuation has peculiar problems. This testing could also provide initial data points for development of the analytical model.

TAP-OFF GAS SPIN-START

Stored thrust-chamber tap-off gases could provide an extremely simple means of restarting an NTO/50-50 spacecraft system. This system would extract fuel-rich gases from the thrust chamber and store them in a pressure bottle for use in a spinning the turbine(s) for the next start. The start-system analysis conducted during this program indicated this concept is feasible for started tap-off gases that have cooled to temperatures as low as 70°F (See Vol. II). This 70°F temperature requirement can probably be accommodated without special provision, since other factors may well require such a temperature environment for the vehicle and/or propulsion system. Further work is required to substantiate these results because this analysis was based on assumptions regarding the properties of the gases after an extended storage time which may not be valid. It was assumed that the gas composition after storage (and cooling) could be determined by extracting heat from the gases in their initial state and determining the new thermochemical equilibrium composition.

Additional work on this concept should consist of a determination of the true gas properties for various storage conditions, and the formulation of a detailed start model to clearly define the conditions under which the concept should be used.

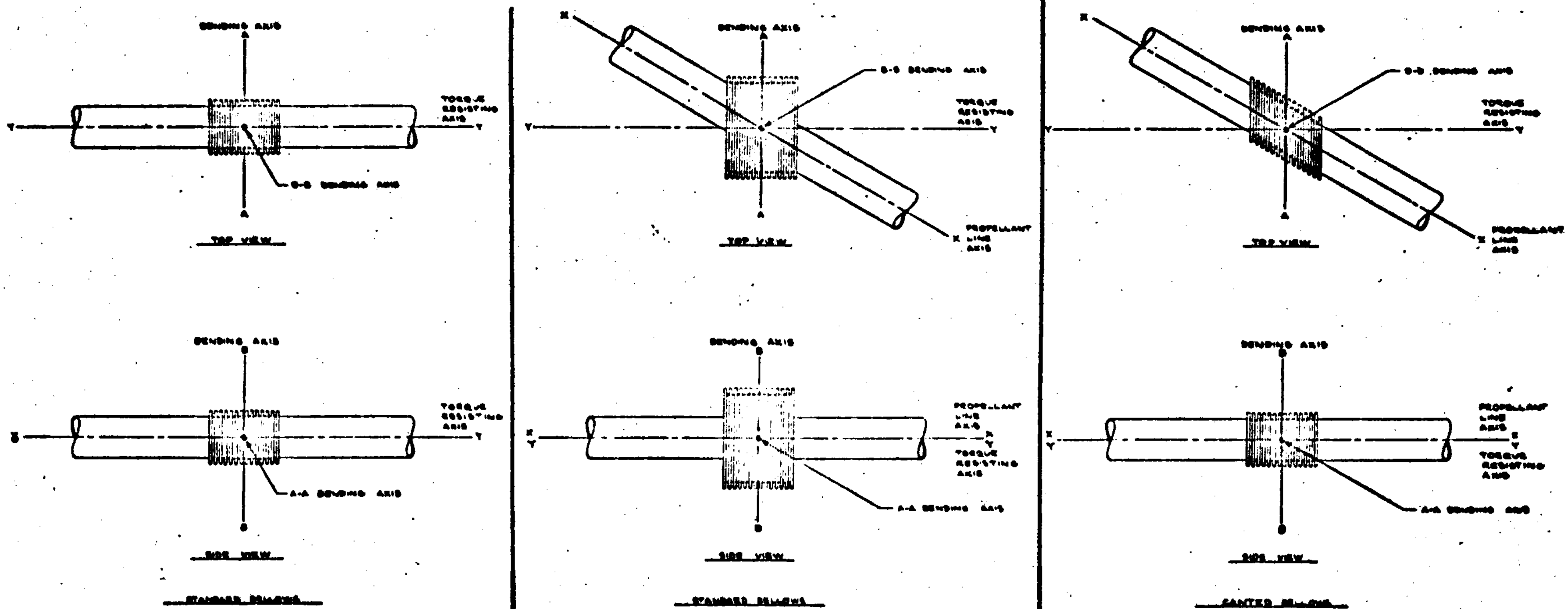
THREE-LEG GIMBAL

Use of the "three-leg" gimbal concept allows ready integration of the gimbal system and propellant inlet ducts while placing the gimbal center close to the propulsion-system center-of-gravity (thus reducing gimbal-actuator loads). In addition, it could provide a more efficient distribution of thrust to the propellant tanks.

Additional work on this concept should consist of dynamical studies to determine the significance of the reduction in actuator loads resulting from the favorable location of the gimbal center, and fabrication of a model for demonstration of feasibility. Effort on this model could also serve to investigate the "canted" bellows concept. Although the "canted" bellows has been used during this program primarily as a part of the "three-leg" gimbal system, it is apparent that its use could substantially simplify some inlet-duct configurations for systems using conventional gimbaling methods.

The purpose of the canted bellows is to allow a flexible joint in a propellant line to bend about axes other than the ones perpendicular to the line axis. Figure 13(a) shows a conventional bellows and line arrangement. The propellant-line and torque-resisting axis is Y-Y. The propellant line can bend about axis A-A and B-B without rotating one half of the line relative to the other. The bellows acts as a constant-velocity universal-joint. Assume it is desired to keep the same bending axes A-A and B-B and torque-resisting axis Y-Y, but change the propellant line axis to X-X as shown in Figure 13(b). This configuration allows the propellant line to be rotated relative to the torque-resisting axis Y-Y. The bending and torque-resisting axes can now be set up independent of the direction of the propellant line, thus allowing greater packaging freedom.

The bellows shown in Figure 13(b) are comparatively large. To reduce the bellows size, the canted bellows shown in Figure 13(c) are used. These bellows combine the smooth propellant flow and small size of the Figure 13(a) bellows and the packaging freedom shown in Figure 13(b).



(a) (b) (c)

Canted Bellows

Figure 13

PULSING ENGINE

A pulsing engine (especially with hypergolic propellants) is potentially more reliable and smaller than a comparable conventional pump-fed system. Should it prove feasible at a reasonable performance level, it could truly provide a system having the more desirable features of both pressure-fed and pump-fed systems.

A further investigation of this concept should be directed at the primary unknowns associated with the concept. These are: (1) combustion performance for pulsing operation, (2) injector-cooling during pulsing operation with high chamber pressures and little or no coolant flow, and (3) feed system and valve dynamics.

The combustion performance investigation could consist of designing and testing low thrust (less than 1000 pounds) injectors to define high-performing configurations. A primary problem would be achieving high performance with a low enough injector pressure-drop to keep the tank pressure low.

Injector cooling while there is no propellant flow during pulsing will probably require novel concepts in injector cooling.

Should promising results be obtained in the above two areas, analytical and design efforts could be initiated to consider feed-system and valve dynamics, and valve design. These efforts would define system and valve configurations for various thrust levels. Novel valve concepts may be required for the larger thrust levels because of the valve cycle-rates required.

REVIEW OF OTHER CONCEPTS

A brief review is presented below of some of the other concepts considered and/or evaluated, but not selected as being among the more promising ones. These are the more interesting of the concepts that were not selected. A complete listing of the concepts considered is presented in the Vol. II summary. The concepts discussed below are:

(1) Tap-off end plates --- a method of extracting turbine-drive gases from large toroidal combustion chambers,

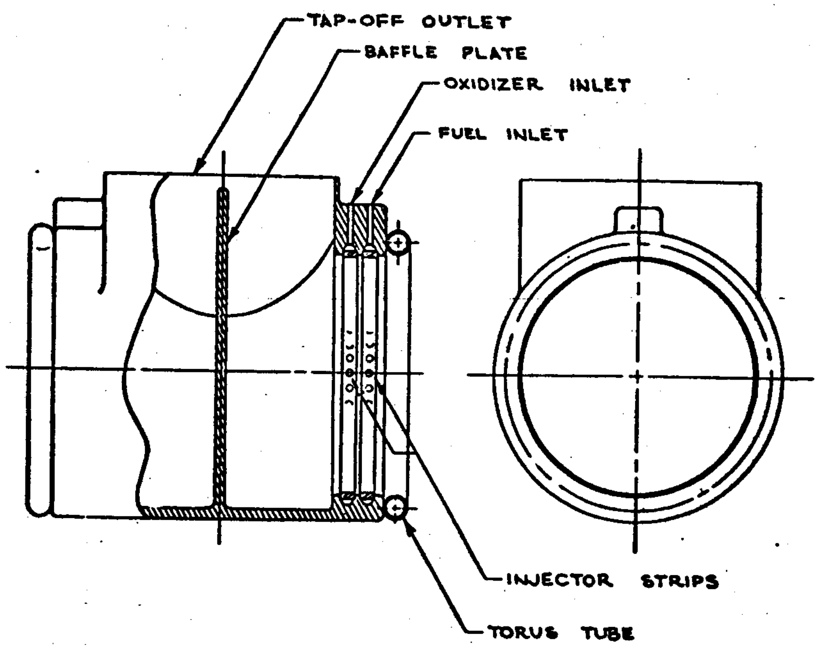
(2) Cartridge turbopump concept --- a modular approach to the packaging of multiple-turbopump systems,

(3) Integrated turbine-spin start-system --- a highly-integrated bi-propellant start-system package for an NTO/50-50 system,

(4) A tubular spherical combustor for low-thrust annular engines which could be used for thrust-vector control.

TAP-OFF END PLATES

The tap-off end plate (Fig. 14) is a concept for extracting turbine-drive gases from a toroidal combustion chamber. It is particularly applicable to large-thrust engines where it could be used to join the segments of a segmented toroidal-combustor as shown in Fig. 5 (b). Thus the tap-off gases would be removed from the end plates thereby eliminating the need



TAP-OFF END PLATE

Figure 14

for a collector manifold along the length of the chamber. As shown in Fig. 14, the end plates could include fuel injectors to reduce the local mixture ratio for turbine operation; or should it be desirable to minimize circumferential gas movement in the combustor, the end plates could contain both fuel and oxidizer injectors, with the propellants injected at the end plates being sufficient for turbine operation. A brief comparison of end plate and other tap-off concepts for toroidal combustors has been made (see Vol. II).

CARTRIDGE TURBOPUMPS

The "cartridge" concept of component integration and packaging is widely used for valves and similar components. The object of this method of packaging is to allow components to have common structural elements, thereby reducing the package size and weight. The extension of this concept to the packaging of turbopumps as shown in Fig. 15 provides similar benefits; in addition it is adaptable to modular packaging for multiple-turbopump configurations, Fig. 16.

BI-PROPELLANT START-SYSTEM

The integrated turbine-spin start-system, Fig. 17, is a highly-integrated, bi-propellant (NTO/50-50) start-system. This compact package includes: propellant start-tanks; gas-generator combustor; closely integrated

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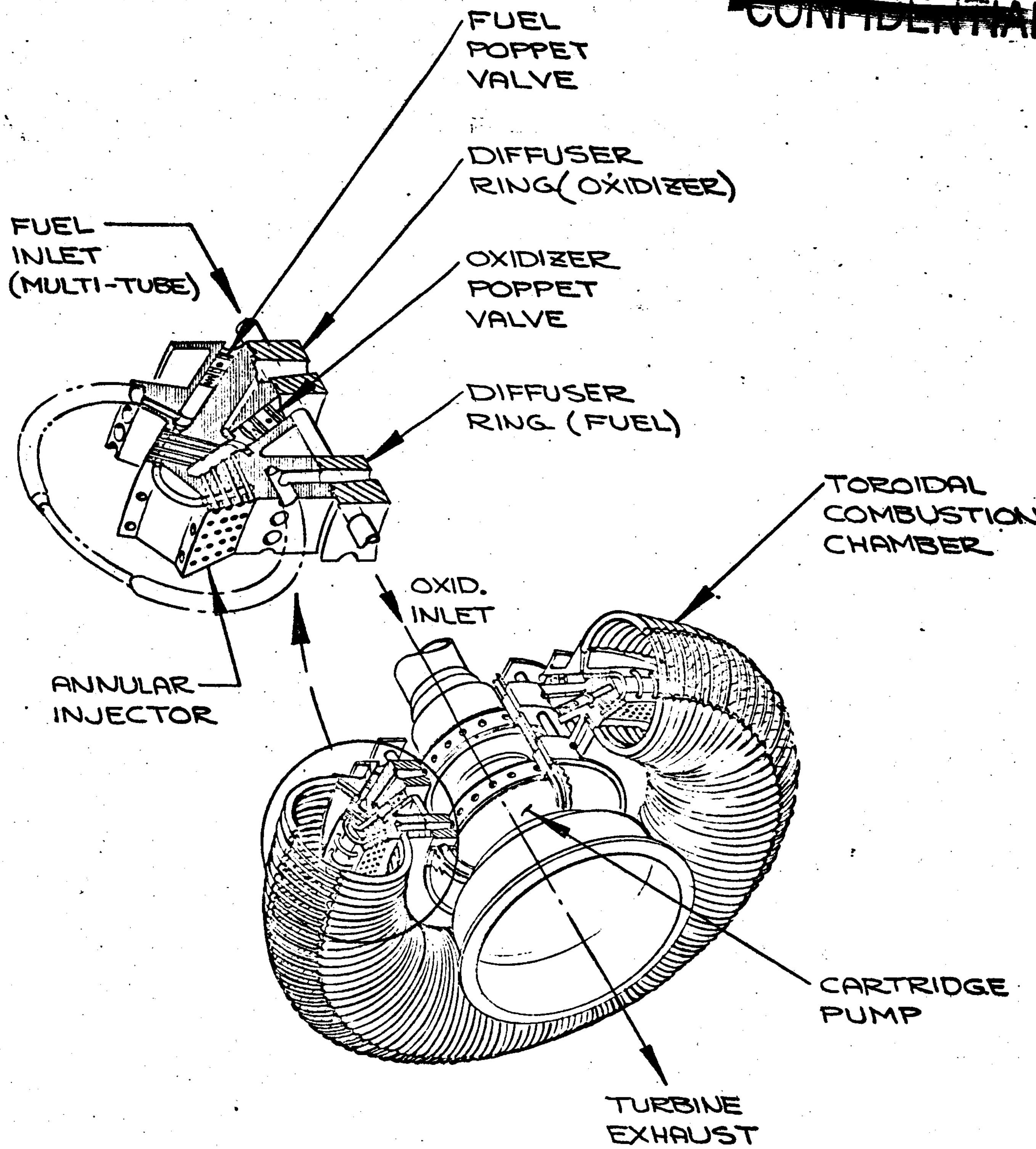

Cartridge Concept, Single Turbopump

Figure 15

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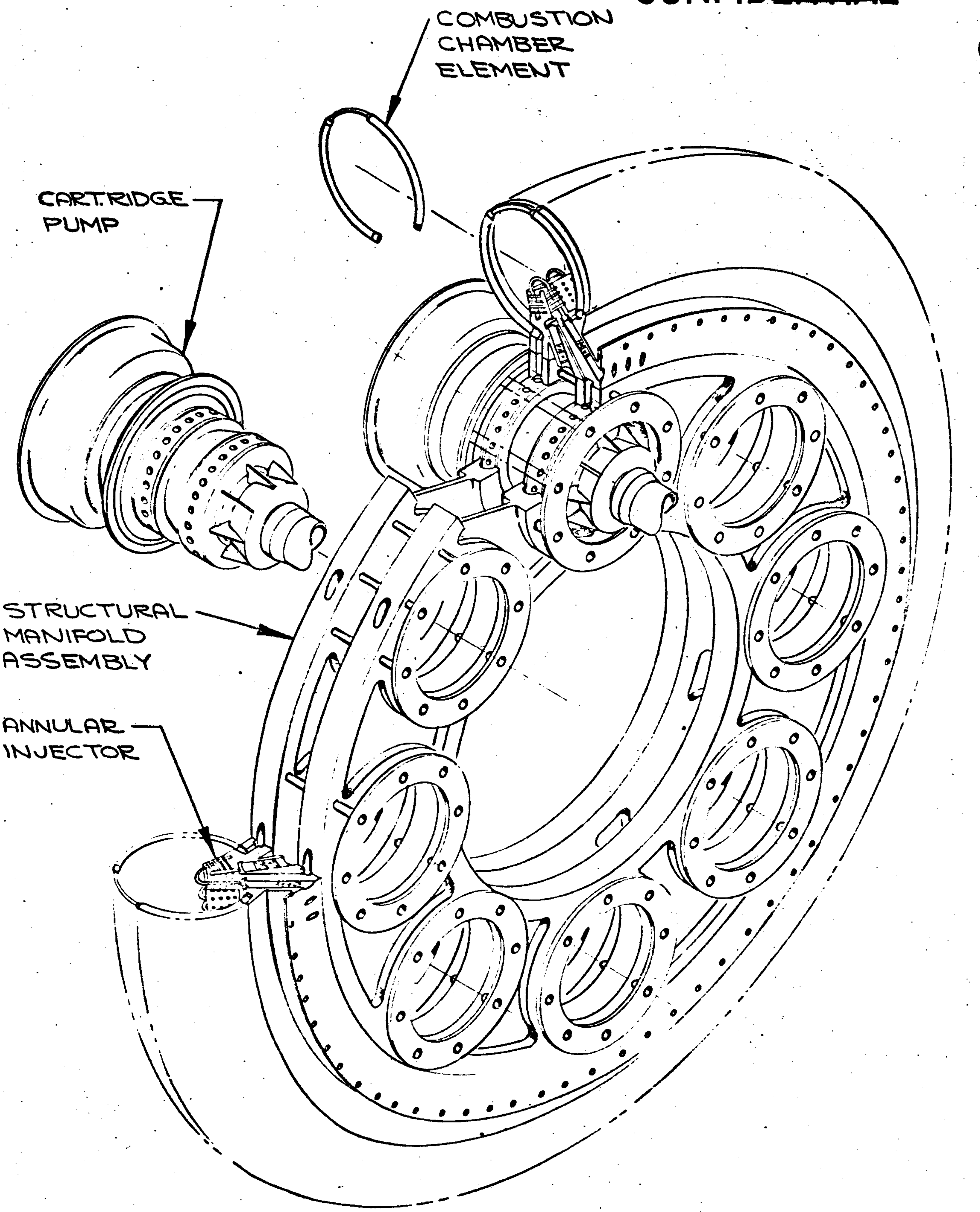
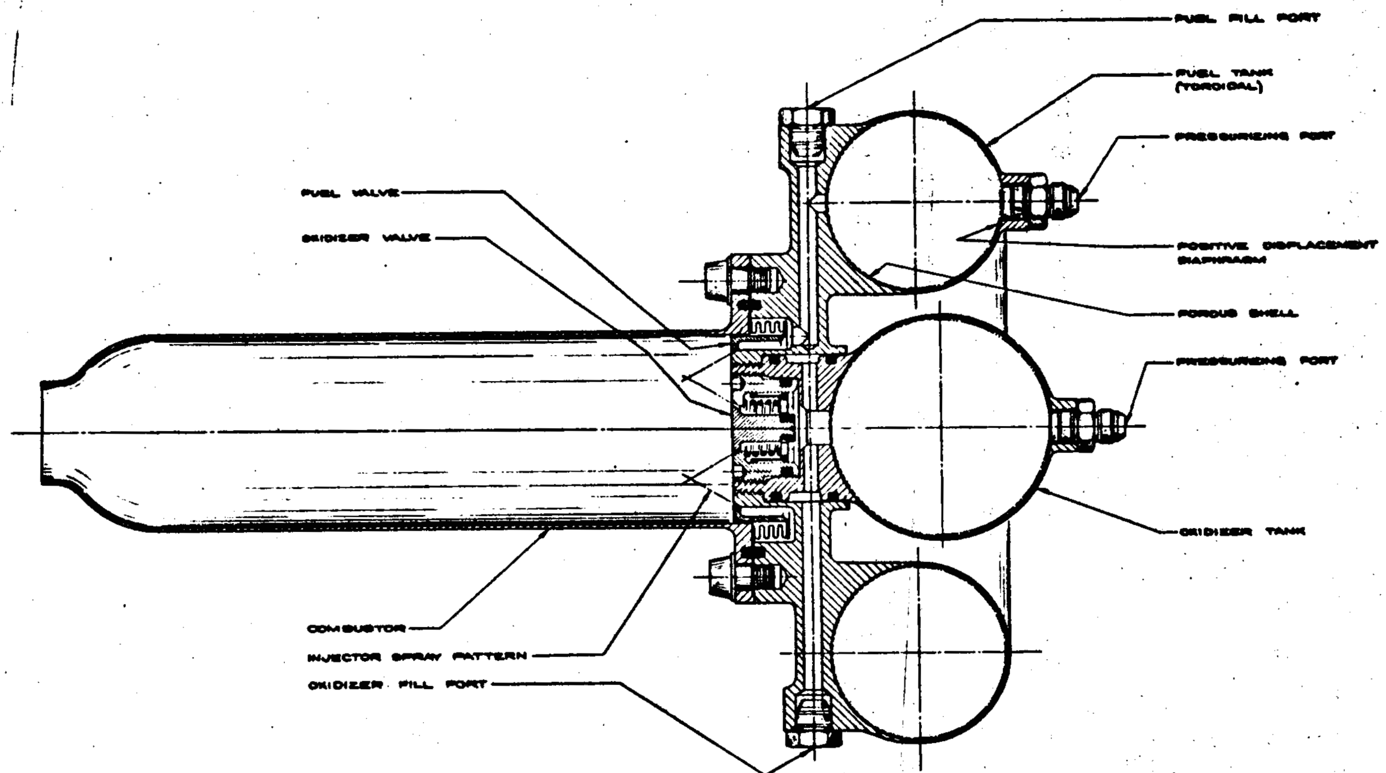


Cartridge Concept, Multiple Turbopumps

Figure 16



Integrated Bi-Propellant Start-System

Figure 17

injector and propellant valves; combined propellant valves and check valves to prevent tap-off gases from flowing into the start system during steady-state operation. This type of start-system could be used, if the tap-off gas spin-start concept should prove infeasible.

TUBULAR SPHERICAL-COMBUSTOR

The tubular spherical-combustor, Figure 18, is an extension of the tubular toroidal-combustor concept to a spherical configuration. As shown in Fig. 18(b), this concept may be usable for thrust vector control. The concept may be especially applicable to low-thrust annular engines.

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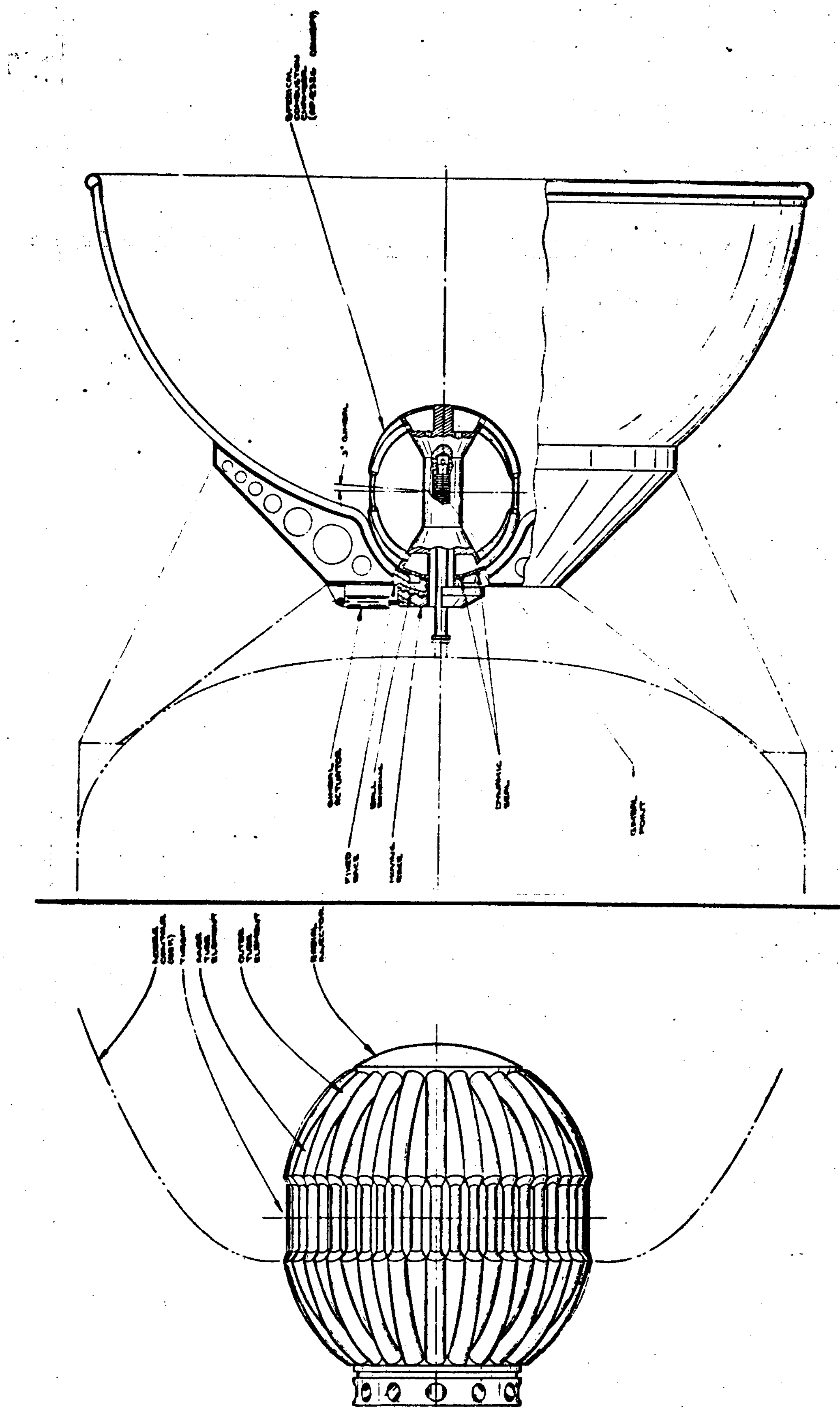

(a) (b)

Tubular Spherical-Combustor

Figure 18

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(1) Martinez, A., et al, Aerodynamic Nozzle Study, Rocketdyne Report R-5381, October 1963.